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Definition of Powers and Power Quality Factors at a Point of Common Coupling in Single-Phase Systems and Three-Phase Systems

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ABSTRACT

This paper proposes an unified definition of powers for various circuit conditions such as balanced/unbalance sinusoidal/non-sinusoidal, and linear/nonlinear, for single-phase systems and three-phase systems. Conventional reacti power is more classified into an interactive power and an alternating power. These powers are defined both in the tir domain and the frequency domain consistently, and agree well with the conservation law. Several important power quali factors are defined to measure and evaluate the power quality for the various circuits in the single-phase and three-pha systems. Simulation results show the power quality factors can evaluate and classify the various circuit conditions clearly

Key Words: Definition, Powers, Power Quality Factors, p-q-r transformation

1. Introduction

Traditionally, active power has been recognized as a useful power that affects energy transfer between subsystems, while reactive power has been regarded as a useless power that only increases the apparent power.

Although the definition of powers is explicit and meaningful in sinusoidal single-phase systems, it becomes ambiguous and ineffective, when the power system becomes multi-phased, distorted, unbalanced, and nonlinear [1]-[3]. Many new ideas have been proposed for these new circuit conditions without getting explicit nor unified definitions [4]-[9].

A three-phase circuit can be handled as three single-phase circuits by transforming a-b-c coordinates to p-q-r coordinates with the use of p-q-r theory [10].

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Thus, an equivalent approach can be applied in definin powers through single-phase systems and three-pha systems. The instantaneous powers defined in p-q coordinates have been analyzed spectrally in the frequenc domain for single-phase systems and three-phase systen [11].

This paper proposes unified definition of powers both i the time domain and in the frequency domain for singl phase systems and three-phase systems. Several pow quality factors are defined to classify and evaluate tl various circuit conditions such as single-phase system three-phase systems, balanced voltages, unbalance voltages, zero-sequence components, harmon components, unbalanced loads, reactive loads, ar nonlinear loads. Simulations of these circuit conditions a done by use of PSIM V4.1.

2. Powers in Time Domain

Fig. 1 shows the generalized circuit that will t analyzed in this paper.

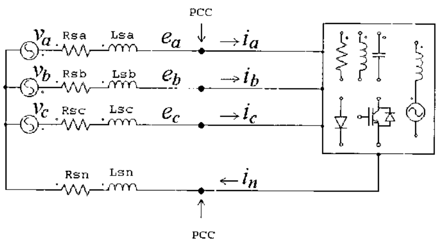


Fig. 1. Analyzed circuit diagram for three-phase four-wire systems.

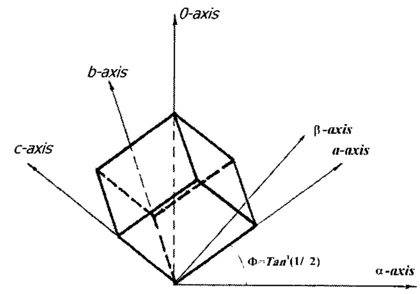


Fig. 2. Physical meaning of 0-α-β transformation.

The system voltages may be balanced, unbalanced or distorted by harmonics. Loads can be any types such as pure resistive loads, reactive loads, single-phase rectifiers, three-phase rectifiers, balanced or unbalanced. The instantaneous powers will be analyzed at the Point of Common Coupling (PCC).

2.1 Coordinate Transformation

Voltages in Cartesian a-b-c coordinates can be transformed to Cartesian 0-α-β coordinates as (1).

$$\begin{bmatrix} e_0 \\ e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Fig. 2 shows the physical meaning of the 0-α-β transformation described in (1). Both in a-b-c coordinates and 0-α-β coordinates, system voltages are represented as a space vector. If the system voltages are sinusoidal and balanced, the voltage space vector rotates counter-clock wise along the circular trace on the α-β plane. When the harmonic components are included in the system voltages, the trace becomes distorted in the α-β plane. Moreover, when a zero-sequence component is included into the system voltages, the trace appears above or under the α-β plane according to the sign of the zero-sequence component.

In Cartesian p-q-r coordinates, the system currents are defined in[10]. The p-q-r coordinates are rotating along with the system voltage space vector.

$$\begin{bmatrix} i_p \\ i_q \\ i_r \end{bmatrix} = \frac{1}{e_{0\alpha\beta}}\begin{bmatrix} e_0 & e_\alpha & e_\beta \\ 0 & -\frac{e_{0\alpha\beta}e_\beta}{e_{\alpha\beta}} & \frac{e_{0\alpha\beta}e_\alpha}{e_{\alpha\beta}} \\ e_{\alpha\beta} & -\frac{e_0 e_\alpha}{e_{\alpha\beta}} & -\frac{e_\beta e_0}{e_{\alpha\beta}} \end{bmatrix}\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

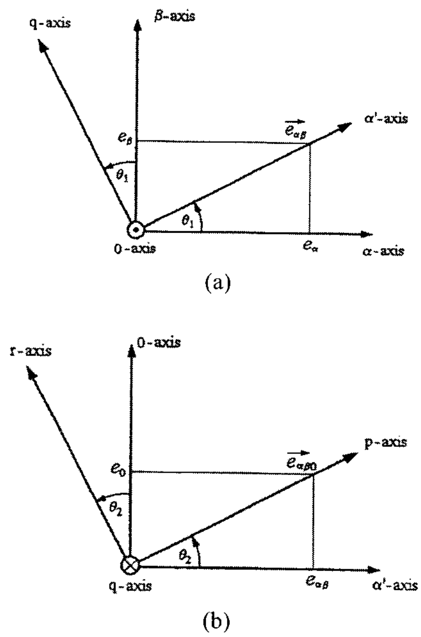
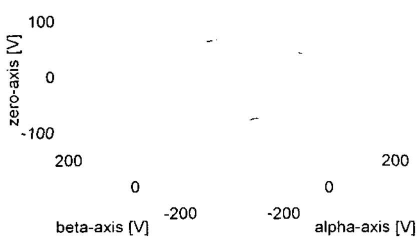


Fig. 3. Physical meaning of p-q-r transformation; (a) q-axis, (b) p-axis and r-axis.

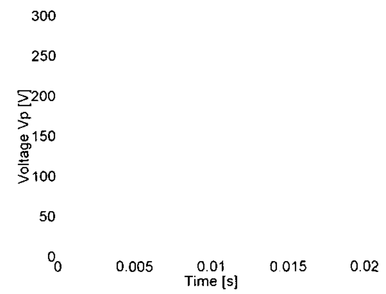
where, $e_{0\alpha\beta} = \sqrt{e_0^2+e_\alpha^2+e_\beta^2}$, $e_{\alpha\beta} = \sqrt{e_\alpha^2+e_\beta^2}$

The physical meaning of p-q-r transformation is shown in Fig. 3. The q-axis is rotating $\theta_1 = Tan^{-1}(e_\beta/e_\alpha)$ from the β-axis according to the ratio e_α and e_β of the voltage space vector. The p-axis is rotating along with the voltage space vector $e_{\alpha\beta0}$. The r-axis is perpendicular to p–axis and q-axis and it oscillates with $\theta_2 = Tan^{-1}(e_0/e_{\alpha\beta})$ from the 0-axis according to the contents of the zero-sequence voltage e_0. The rotating speed of the p-q-r coordinates varies according to that of the voltage space vector.

In p-q-r coordinates, the system voltages are defined by (3). The voltage exists only in the p-axis.



(a)



(b)

Fig. 4. Comparison of a typical voltage expression when 5^{TH}(=20%) and 7^{TH}(=14%) order harmonics are included in the system voltage in 3-phase 4-wire systems; (a) in 0-α-β coordinations, (b) in p-q-r coordinates where only a voltage in the p-axis exists.

$$\begin{bmatrix} e_p \\ e_q \\ e_r \end{bmatrix} = \frac{1}{e_{0\alpha\beta}} \begin{bmatrix} e_0 & e_\alpha & e_\beta \\ 0 & -\frac{e_{0\alpha\beta}e_\beta}{e_{\alpha\beta}} & \frac{e_{0\alpha\beta}e_\alpha}{e_{\alpha\beta}} \\ e_{\alpha\beta} & -\frac{e_0 e_\alpha}{e_{\alpha\beta}} & -\frac{e_\beta e_0}{e_{\alpha\beta}} \end{bmatrix} \begin{bmatrix} e_0 \\ e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} e_{0\alpha\beta} \\ 0 \\ 0 \end{bmatrix} \quad (3)$$

Fig. 4 compares typical voltage expression between 0-α-β coordinates and p-q-r coordinates. Although there are three voltage components in 0-α-β coordinates, only one voltage component e_p exists in p-q-r coordinates. The voltage e_p comprises a dc component e_{pdc} and an ac component e_{pac}. The fundamental forward-sequence component of the system voltages is transformed into the e_{pdc}. The fundamental reverse-sequence component of the system voltages is transformed into the 2^{ND} order frequency component of the e_{pac}. The zero-sequence or harmonic components of the system voltages are transformed into the higher even-order frequency components of the e_{pac}.

In a single-phase system, the voltage and current in the p-q-r coordinates can be calculated as (4) through (6).

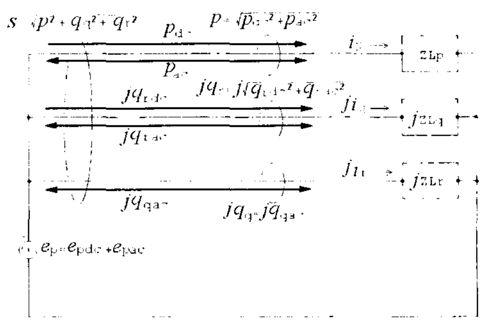


Fig. 5. Equivalent circuit diagram and power flow in p-q-coordinates.

In this case, the voltage e_p and current i_p have only odd order frequency components without a dc component. A single-phase system has only a p-circuit.

$$e_p = e_a \quad (4)$$

$$i_p = i_a \quad (5)$$

$$e_q = e_r = i_q = i_r = 0 \quad (6)$$

2.2 Definition of Powers In Time Domain

Instantaneous real power p and the instantaneous imaginary power q_q, q_r are defined as (7).

$$\begin{bmatrix} p \\ q_q \\ q_r \end{bmatrix} = \begin{bmatrix} e_p i_p \\ -e_p i_r \\ e_p i_q \end{bmatrix} \quad (7)$$

The instantaneous imaginary powers q_q, q_r can be compensated without using any energy storage element such as capacitors [10][11].

Fig. 5 shows the equivalent circuit diagram and the power flow in p-q-r coordinates. The three-phase system voltages are transformed into the single-phase source voltage e_p that comprises a dc component e_{pdc} and an ac component e_{pac}. The three circuits, completely separated from each other, are just connected in parallel to the source voltage e_p. The notation "j" means the imaginary part that is perpendicular to p-axis.

The three instantaneous powers are linearly independent of each other, and each instantaneous power can be analyzed in the same way as for single-phase systems.

Table 1. Definition of Instantaneous Powers.

Definition	Description
$\overline{p} \equiv p_{dc}$	Instantaneous active power
$\overline{q} \equiv q_{rdc}$	Instantaneous interactive power
$z_p \equiv p_{ac}$	p-axis instantaneous alternating power
$z_q \equiv q_q$	q-axis instantaneous alternating power
$z_r \equiv q_{rac}$	r-axis instantaneous alternating power
$z \equiv \sqrt{p_{ac}^2+q_q^2+q_{rac}^2}$	Instantaneous alternating power
$s \equiv \|\vec{e}\|\cdot\|\vec{i}\| = \sqrt{p^2+q_q^2+q_r^2} \equiv \sqrt{p^2+q^2+z^2}$	Instantaneous apparent power

Instantaneous powers can be defined in the time domain as given in Table I. Instantaneous active power $\overline{p}$ is effectively transferred between two subsystems.

Three-phase reactive currents interact with other phase voltages and are producing an instantaneous interactive power $\overline{q}$ in a balanced/sinusoidal three-phase system. The instantaneous interactive power $\overline{q}$ increases the instantaneous apparent power s. If the circuit-components are inductive dominant, the sign of $\overline{q}$ becomes positive. Conversely, if the circuit-components are capacitive dominant, the sign of $\overline{q}$ becomes negative. The instantaneous interactive power $\overline{q}$ can be exchanged among the three phases and compensated to zero without using any energy storage element.

Instantaneous alternating power z is useless power that only increases the instantaneous apparent power s. It comes from various non-ideal circuit conditions such as unbalanced or distorted source voltages and/or unbalanced or nonlinear loads. Because of p-axis instantaneous alternating power z_p, the instantaneous alternating power z can be compensated only by using energy storage element such as power capacitors.

3. Powers in Frequency Domain

3.1 Fourier Analysis of Instantaneous Power

When DC and harmonic components are considered, the voltage and current in a single-phase system can be described as (8) and (9). All the variables in the frequency domain or constants are described as upper case: Instantaneous variables in the time domain are describe as lower cases.

$$e(t) = E_{DC} + \sum_{n=1}^{N_t} \sqrt{2}E_n \sin(n\omega t - \Phi_{en}) \quad (8$$

$$i(t) = I_{DC} + \sum_{n=1}^{N_t} \sqrt{2}I_n \sin(n\omega t - \Phi_{in}) \quad (9$$

With the voltage and current described in (8) and (9), th instantaneous power can be calculated as (10).

$$\begin{aligned} p &= e(t)\cdot i(t) \\ &= E_{DC}I_{DC} + \sum_{n=1}^{N_t} E_n I_n \cos\{\Phi_{en} - \Phi_{in}\} \\ &+ E_{DC}\left(\sum_{n=1}^{N_t} \sqrt{2}I_n \sin\{n\omega t - \Phi_{in}\}\right) \\ &+ I_{DC}\left(\sum_{n=1}^{N_t} \sqrt{2}E_n \sin\{n\omega t - \Phi_{en}\}\right) \\ &+ \sum_{k=2}^{N_t}\sum_{n=1}^{k-1} E_k I_n \cos\{(k-n)\omega t - (\Phi_{ek} - \Phi_{in})\} \\ &+ \sum_{k=1}^{N_t}\sum_{n=k+1}^{N_t} E_k I_n \cos\{(n-k)\omega t + (\Phi_{ek} - \Phi_{in})\} \\ &- \sum_{k=1}^{N_t}\sum_{n=1}^{N_t} E_k I_n \cos\{(k+n)\omega t - (\Phi_{en} + \Phi_{in})\} \end{aligned} \quad (10$$

Equation (10) is comprised with 6 terms, each of then has power cells that are combinations of a certain part o the voltage and the current in (8) and (9) according to th frequency.

When up to the 6^{th} harmonic voltages and the 9^{t} harmonic currents are considered, the generated powe cells are distributed spectrally as in Table 2 according t (10).

The numbers written on the vertical axis describe th frequency orders of the generated power cells. Th numbers written on the horizontal axis describe th frequency orders of the current components. The number written on each power cell describe the frequency order o the voltage components. The power cells with a sam frequency order are summed up to produce the sam frequency component of the instantaneous powers p, q_q, o q_r.

'able 2. Special analysis of the generated power cells with a onlinear loads

Frequency Order of Power Compon.	Frequency Order of Current components																		
	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9
8																			1
7																		1	2
6																	1	2	3
5																1	2	3	4
4															1	2	3	4	5
3														1	2	V	4	5	6
2													1	2	3	4	5	6	
1												1	2	3	4	5	6		
0										0	1	2	3	I	5	6			
1								II*(q_q)=>	0		2	3	4	5	6				
2							II*(p, q_r)=>	0	1	2	3	IV	5	6					
3							0	1	2		4	5	6						
4						0	1	2	3	4	5	6							
5					II	1	2	3	4	III	6								
6				0	1	2	3	4	5	6									
7			0	1	2	VI	4	5	6										
8		0	1	2	3	4	5	6											
9	0	1	2	3	4	5	6												
10	1	2	3	4	5	6													

3.2 Spectral Analysis of Power Cells

In case of three-phase systems, the power cells are ;enerated only by the even-order frequency of the voltage e_p. Conversely, in case of single-phase systems, the power :ells are generated only by the odd-order frequency of the /oltage e_p. Moreover in single-phase systems, only nstantaneous real power p exists.

The instantaneous real power p and the r-axis nstantaneous imaginary power q_r contains only even order frequency components since i_p and i_q have only even order frequency current components in three-phase systems. Conversely, the q-axis instantaneous imaginary power q_q contains only odd order frequency components since i_r has only odd order frequency components in three-phase systems.

In single-phase systems, the instantaneous real power p also has only even order frequency components since both the current i_p and the voltage e_p have only odd order frequency components.

If the loads are linear elements such as resistors, inductors or capacitors, the current has limited orders of frequency. But if the loads are nonlinear such as rectifiers, the current has unlimited order of frequency so that the number of power cells become infinite. Table II comprises 6 regions according to (10).

Power Cells in Region I

Region I corresponds to the first term of (10), that is constant value of the instantaneous powers. In case of the instantaneous real power p, this region relates with traditional active power in three-phase systems. In case of the r-axis instantaneous imaginary power q_r, this region relates with traditional reactive power in three-phase systems. This region does not exist in the q-axis instantaneous imaginary power q_q.

Region I comprises two parts. One part marked with 0 comes from the forward-sequence component of the system voltage e_p which is related with so called forward-sequence active or interactive power. The other part marked with 1, 2, 3, 4, 5, and 6 comes from the various frequency components of the system voltage e_p which is related with so called distortion active or interactive power Here, the newly defined interactive power can be compensated to zero among the three-phase lines without using energy storage element.

In normal three-phase systems, the major part is the forward-sequence active or interactive power. The forward-sequence active power produces pure rotating torque on three-phase rotating machines. The forward-sequence interactive power provides necessary reactive currents to reactive loads such as inductors, capacitors, or induction motors/ generators in three-phase systems. The distortion active or interactive power exerts bad effects on three-phase rotating machines such as over heating, vibration, speed fluctuation. If the loads are resistive such as heaters or light bulbs, the distortion active power is alsc useful. In general, the distortion active power is an infinite sum of power cells according to the frequency components of the voltage e_p.

As mentioned before, only even-order components of the voltage e_p exist in three-phase systems. The active power cell marked by 2 comes from the unbalancec system voltages that rotates reverse-sequence. The othe active power cells marked by 4 and 6 come from the harmonic voltage components that cause vibration on the three-phase rotating machines.

In case of single-phase systems, only odd-orde frequency components of the voltage e_p exist, whicl generate only the instantaneous real power p. Since there is no power cell marked by "0", the active power comprises only the distortion active power in single-phase systems.

The active power cell marked by 1 is normally a major part, the other active power cells marked by 3, 5 come from the harmonic voltages in single-phase systems. It is certain that there is no forward-sequence active power in single-phase systems. Thus single-phase systems can be considered as a pure unbalanced system.

Power Cells in Region II

Region II corresponds to the second term of (10). This region does not exist in single-phase systems. This region occurs when the system voltages are sinusoidal/balanced but the loads are unbalanced (marked by II*) or nonlinear (not marked) in three-phase systems.

The power cell marked by "II*(p,q_r)" appears in the instantaneous real power p and the r-axis instantaneous imaginary power q_r when the loads are unbalanced in three-phase systems. Besides, the power cell marked by "II*(q_q)" appears to the q-axis instantaneous imaginary power q_q when the loads are unbalanced in three-phase systems.

Power Cells in Region III

Region III corresponds to the third term of (10). This region exists only for the instantaneous real power p and the r-axis instantaneous imaginary power q_r in three-phase systems. This region is generated by the multiplication of a sinusoidal/balanced current components and a unbalanced system voltage (marked by 2) or harmonic system voltages (marked by 4 and 6).

Power Cells in Region IV

Region IV corresponds to the 4^{TH} term of (10). This region exists both in three-phase and single-phase systems. In this region, the frequency order of the current are always lower than that of the voltage in every power cell.

The frequency order of the each power cell is the difference of the frequency orders between the current and voltage. The power cell marked by the shaded "2" appears to the q-axis instantaneous imaginary power q_q when the loads are unbalanced in three-phase systems.

Power Cells in Region V

Region V corresponds to the 5^{TH} term of (10). Thi: region exists both in three-phase and single-phase system: In this region, the frequency order of the current ar always higher than that of the voltage in every power cell: The frequency order of the each power cell is th difference of the frequency orders between the current an voltage.

Power Cells in Region VI

Region VI corresponds to the last term of (10). Thi: region exists both in three-phase and single-phase system: In this region, the frequency order of the each produce power cell is the sum of the frequency orders of th current and voltage.

The power cell marked by the shaded "1" appears to th instantaneous real power p by the fundamenta components of the voltage and current in single-phas systems. The power cell marked by shaded "2" appears t the q-axis instantaneous imaginary power q_q when th power system is unbalanced in three-phase systems.

Regions II, III, IV, V, and VI do not contribute to th energy transfer between the sub-systems, but increase th instantaneous apparent power. This requires larger utilit equipment, causes more transfer losses on the grids an degrades the power quality on the power systems. Amon these regions, the regions II and III are usually dominan parts.

To get a more practical view, each current componen and power component of the same frequency in Table : must be combined as shown in Table 3, Table 4, and Tabl 5: the region V is folded vertically to the region IV, an the regions II and VI are folded horizontally to the regio IV. The shaded power cells in the Tables 3, 4 and 5 ar related with the unbalance in the power systems.

Table 3 shows the spectral distribution of the generate power cells for the instantaneous real power p and for th r-axis instantaneous imaginary power q_r in three-phas systems.

In three-phase systems, the voltage e_p has only eve order frequency components. As shown in the Table 2, th instantaneous real power p and the r-axis instantaneou imaginary power q_r contains only even order frequenc components since i_p and i_q have also only even orde frequency components.

Table 3. Special analysis of the generated power cells for p and qr in three-phase systems.

	0	1	2	3	4	5	6	7	8	9
0	0		2		4		6			
1										
2	2		4/0		6/2		4		6	
3				II						
4	4		6/2		0		2		4	
5										
6	6		4		2		0		2	

Table 4. Special analysis of the generated power cells for qq in three-phase systems.

	0	1	2	3	4	5	6	7	8	9
0										
1		2/0		4/2		6/4		6		
2			II							
3		4/2		6/0		2		4		6
4			IV							
5		6/4		2		0		2		4
6										

Table 5. Special analysis of the generated power dells for p in single-phase systems.

	0	1	2	3	4	5	6	7	8	9
0		1		3		5				
1										
2		3/1		5/1		3		5		
3										
4		5/3		1		1		3		5
5										
6		5		3		1		1		3

As shown in the Table 4, the q-axis instantaneous imaginary power q_q contains only odd order frequency components since i_r has only odd order frequency components. There is no dc power component in the q-axis instantaneous imaginary power q_q.

As shown in the Table 5, only the instantaneous real power p exists in single-phase systems. Thus, the power cells are generated only on even order frequencies since the current i_p and the voltage e_p have only odd order frequency components.

Table 6. Definition of some important power components

*	Definition	Description
	$P \equiv p_{dc}$	Active power.
	$P_f \equiv E_{pdc} \cdot I_{pdc}$	Forward-seq. active power in three-phase systems.
	$P_f \equiv E_{p1} \cdot I_{p1} \cdot \cos\Phi_{p1}$	Fundamental active power in single-phase systems.
	$P_d \equiv P - P_f$	Distortion active power.
	$P_r \equiv E_{p2} \cdot I_{p2} \cdot \cos\Phi_{p2}$	Reverse-seq. active power.
	$P_h \equiv P_d - P_r$	Harmonic active power.
	$Q \equiv q_{rdc}$	Interactive power.
	$Q_f \equiv E_{pdc} \cdot I_{qdc}$	Forward-sequence interactive power.
	$Q_d \equiv Q - Q_f$	Distortion interactive power
	$Q_r \equiv E_{p2} \cdot I_{q2} \cdot \cos\Phi_{q2}$	Reverse-sequence interactive power.
	$Q_h \equiv Q_d - Q_r$	Harmonic interactive power
II III IV V VI	$Z_p \equiv \sqrt{\sum_{k=2,4,6} P_k^2}$	p-axis alternating power.
	$Z_q \equiv \sqrt{\sum_{k=1,3,5} Q_{qk}^2}$	q-axis alternating power.
	$Z_r \equiv \sqrt{\sum_{k=2,4,6} Q_{rk}^2}$	r-axis alternating power.
	$Z \equiv \sqrt{Z_p^2 + Z_q^2 + Z_r^2}$	Alternating power.
all	$R \equiv \sqrt{Q^2 + Z^2}$	Reactive power.
	$S \equiv \sqrt{P^2 + Q^2 + Z^2}$	Apparent power.

* Related regions shown in Table 2.

** Φ : Phase angle between the voltage and current components a the same frequency order.

*** Subscript number describes the frequency order.

3.3 Definition of Powers In Frequency Domain

Based from the spectral analysis of the power cells sc far, some important power components can be defined ir the frequency domain as shown in Table 6 for single-phase systems and three-phase systems.

An active power P is defined as the average value of the instantaneous real power p_{dc}, that is equal to the instantaneous active power $\overline{p}$. The active power P comprises a forward-sequence (or fundamental) active power P_f and a distortion active power P_d. The forward sequence active power is defined as P_f in three-phase systems. However, since there is no forward-sequence active power, the fundamental active power is defined as P_f in single-phase systems. The distortion active power P_d comprises a reverse-sequence active power P_r and a harmonic active power P_h in three-phase systems, whereas it comprises only the harmonic active power P_h in single-phase systems.

In normal three-phase systems, the forward-sequence active power P_f is the major part. The forward-sequence active power P_f produces a pure rotating-torque on three-phase rotating machines. The reverse-sequence active power P_r results in a torque fluctuation with a double rotating frequency. The harmonic active power exerts also bad effects on three-phase rotating-machines such as over-heating, vibrating, and fluctuating. When the loads are resistive such as heaters or light bulbs, the distortion active power is also useful.

A reactive power R is defined as a geometrical sum of an interactive power Q and an alternating power Z. The interactive power Q is defined by the average value of the r-axis instantaneous imaginary power q_{rdc}, that is equal to the instantaneous interactive power $\bar{q}$. The alternating power Z is defined by the geometric sum of the ac components of all the instantaneous powers p_{ac}, q_q ($=q_{qac}$), and q_{rac}. The reactive power in single-phase systems comprises only a p-axis alternating power Z_p.

The interactive power Q exists only in three-phase systems, and it comprises a forward-sequence interactive power Q_f and a distortion interactive power Q_d. The forward-sequence interactive power Q_f provides necessary reactive currents to the reactive loads such as inductors, capacitors, or induction motors/generators in three-phase systems. The distortion interactive power Q_d can be classified into a reverse-sequence interactive power Q_r that results from unbalance, and a harmonic interactive power Q_h that results from harmonics.

It is important to note that the traditional reactive power defined in sinusoidal single-phase systems is associated in the p-axis alternating power Z_p, whereas the traditional reactive power defined in sinusoidal balanced three-phase systems is associated in the forward-sequence interactive power Q_f. This is physically true since the traditional reactive power defined in sinusoidal balanced three-phase systems can be compensated without using any energy storage element, while the traditional reactive power defined in sinusoidal single-phase systems can be compensated only by using energy storage elements such as power capacitors.

In fact, single-phase systems can be regarded as unbalanced systems since all the three symmetrical components (forward-sequence, reverse-sequence, and zero-sequence) of the voltage or current are equal to 1/3 times of the rms voltage and rms current respectively in single-phase systems.

3.4 Decomposing Alternating Power

The alternating power Z can be further decomposed into an unbalanced alternating power Z_u and a harmonic alternating power Z_h. In three-phase systems, the p-axis instantaneous unbalanced alternating power $\tilde{p}_{ub}$ occurs from the interaction between the DC and 2ND order frequency components of the voltage e_p and the current i_p. So that the p-axis instantaneous unbalanced alternating power $\tilde{p}_{ub}$ can be calculated in the time domain as (11) according to (10). Then the unbalanced p-axis alternating power Z_{pub} can be calculated in the frequency domain as (14) by the magnitude of the p-axis instantaneous unbalanced alternating power $\tilde{p}_{ub}$. In the same way, the r-axis unbalanced alternating powers $\tilde{q}_{rub}$ and Z_{rub} can be calculated as (13) and (16) respectively.

The q-axis instantaneous unbalanced alternating power $\tilde{q}_{qub}$ occurs from the interaction between the DC and 2ND order frequency component of the voltage e_p and the 1ST order frequency component of the current i_r. Thus, the q-axis unbalanced alternating powers $\tilde{q}_{qub}$ and Z_{qub} can be calculated as (12) and (15) respectively.

$$\begin{aligned}\tilde{p}_{ub} &= \sqrt{2}E_{pdc}I_{p2}\sin(2\omega t-\Phi_{p2}) \\ &+\sqrt{2}E_{p2}I_{pdc}\sin 2\omega t - E_{p2}I_{p2}\cos(4\omega t-\Phi_{p2})\end{aligned} \quad (11)$$

$$\begin{aligned}\tilde{q}_{qub} &= \sqrt{2}E_{pdc}I_{r1}\sin(\omega t-\Phi_{r1}) \\ &+E_{p2}I_{r1}\cos(\omega t+\Phi_{r1}) - E_{p2}I_{r1}\cos(3\omega t-\Phi_{r1})\end{aligned} \quad (12)$$

$$\begin{aligned}\tilde{q}_{rub} &= \sqrt{2}E_{pdc}I_{q2}\sin(2\omega t-\Phi_{q2}) \\ &+\sqrt{2}E_{p2}I_{qdc}\sin 2\omega t - E_{p2}I_{q2}\cos(4\omega t-\Phi_{q2})\end{aligned} \quad (13)$$

$$\begin{aligned}Z_{pub} &= \sqrt{\begin{aligned}&2(E_{pdc}I_{p2})^2+2(E_{p2}I_{pdc})^2 \\ &+4(E_{pdc}I_{p2})(E_{p2}I_{pdc})\cos\Phi_{p2}+(E_{p2}I_{p2})^2\end{aligned}} \\ &\cong P_2\end{aligned} \quad (14)$$

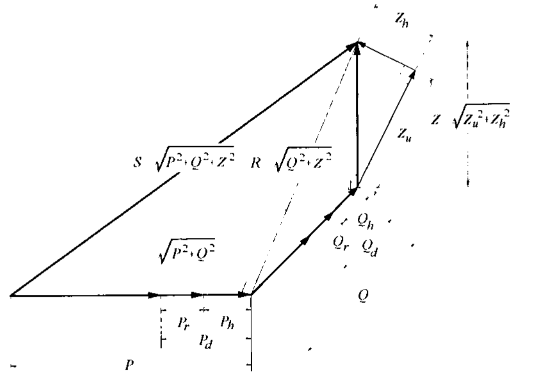


Fig. 6. Physical meaning of the power definition in the frequency domain.

$$Z_{qub} = \sqrt{\begin{aligned}&2(E_{pdc}I_{r1})^2 + 2(E_{p2}I_{r1})^2 \\ &- 2\sqrt{2}(E_{pdc}I_{r1})(E_{p2}I_{r1})\sin 2\Phi_{r1}\end{aligned}} \cong Q_{q1} \tag{15}$$

$$Z_{rub} = \sqrt{\begin{aligned}&2(E_{pdc}I_{q2})^2 + 2(E_{p2}I_{qdc})^2 \\ &+4(E_{pdc}I_{q2})(E_{p2}I_{qdc})\cos\Phi_{q2} + (E_{p2}I_{q2})^2\end{aligned}} \cong Q_{r2} \tag{16}$$

In single-phase systems, the p-axis instantaneous unbalanced alternating power component $\tilde{p}_{1ub}$ occurs from the interaction between the 1^{ST} frequency components of the voltage e_p and the current i_p. So that the p-axis instantaneous unbalanced alternating power $\tilde{p}_{1ub}$ can be calculated in the time domain as (17) according to (10). The p-axis unbalanced alternating power Z_{pub} that is equal to the unbalanced alternating power Z_u can be calculated in the frequency domain as (18) by the magnitude of the p-axis instantaneous unbalanced alternating power $\tilde{p}_{1ub}$.

$$\tilde{p}_{1ub} = -E_{p1}I_{p1}\cos(2\omega t - \Phi_{p1}) \tag{17}$$

$$Z_u = Z_{pub} = E_{p1}I_{p1} \cong P_2 \tag{18}$$

Now, the unbalanced alternating power Z_u and the harmonic alternating power Z_h can be defined as (19) and (20) respectively in both single-phase and three-phase systems.

Table 7. Definition of power quality factors.

Definition	Description
$\text{DISF} \equiv P_f \,/\, \sqrt{P_f^2 + Q_f^2}$	Fundamental displacement factor in three-phase systems.
$\text{DISF} \equiv \dfrac{P_{1f}}{E_{p1}\cdot I_{p1}} = \cos\Phi_{p1}$	Fundamental displacement factor in single-phase systems.
$\text{APDF} \equiv P_d \,/\, P_f$	Active power distortion factor.
$\text{APRF} \equiv P_r \,/\, P_f$ *	Active power reverse factor.
$\text{APHF} \equiv \text{APDF} - \text{APUF}$	Active power harmonic factor.
$\text{TPDF} \equiv \sqrt{P_d^2 + Q_d^2 + Z^2} \,/\, S$	Total power distortion factor.
$\text{TPUF} \equiv \sqrt{P_r^2 + Q_r^2 + Z_u^2} \,/\, S$ *	Total power unbalance factor.
$\text{TPHF} \equiv \sqrt{P_h^2 + Q_h^2 + Z_h^2} \,/\, S$	Total power harmonic factor.
$\text{FPTF} \equiv P_f \,/\, S$	Forward-seq. power transfer factor.
$\text{TPTF} \equiv P \,/\, S$	Total power transfer factor.

*: This factor cannot defined in single-phase systems.

$$Z_u \equiv \sqrt{Z_{pub}^2 + Z_{qub}^2 + Z_{rub}^2} \tag{19}$$

$$Z_h \equiv \sqrt{Z^2 - Z_u^2} \tag{20}$$

Fig. 6 shows the physical meaning of the proposed definition of powers in the frequency domain. The reactive power R comprises the interactive power Q and the alternating power Z in three-phase systems. There is only an alternating power Z in the reactive power Q in single phase systems.

4. Power Quality Factors

Based on the power definition in the frequency domain so far, several important power quality factors are defined as in Table 7.

The definition of the power quality factors is consistent through three-phase systems and single-phase systems. The only difference occurs in the definition of the fundamental displacement factor (DISF). The DISF describes the angle between the fundamental component of the voltage and current. This factor is equal to the traditional power factor cosΦ in ideal single-phase systems or ideal three-phase systems. But the DISF can be defined in any circuit conditions such as linear or nonlinear loads, balanced or unbalanced conditions in single-phase or three-phase systems.

The active power distortion factor (APDF) shows how much useless distorted active power P_d that gives harmful effects on rotating machines is contained in the active power P. The APDF may come from the reverse-sequence active power P_r and/or the harmonic active power P_h. The active power reverse factor (APRF) evaluates how much reverse-sequence active power P_r exists in relation to the forward-sequence active power P_f. The active power harmonic factor (APHF) measures how much harmonic active power P_h exists in relation to the forward-sequence active power P_f. In ideal case, these values must be zero.

The total power distortion factor (TPDF) describes all the distortions from the active power, interactive power, and the alternating power, which are all useless and only increase the apparent power S. The TPDF comes from the voltage and current that are unbalanced or distorted by harmonics. The total power unbalance factor (TPUF) shows all the power distortions resulting from the unbalanced voltage or current. The total power harmonic factor (TPHF) evaluates all the power distortions resulting from the harmonics of the voltage or current. In the ideal case, all these factors TPDF, TPUF and TPHF must be zero.

The forward-sequence power transfer factor (FPTF) measures how much forward-sequence active power P_f is contained in the apparent power S. Thus, the FPTF is important in the application of rotating machines.

The total power transfer factor (TPTF) describes how much total active power P is contained in the apparent power S. The TPTF is equal or larger than the FPTF. A large value of the total power distortion factor TPDF means small values of both the FPTF and TPTF, since the TPDF evaluates how much useless power is contained in the apparent power.

5. Simulations

To evaluate various circuit conditions such as single-phase/three-phase systems, linear/non-linear loads, balanced/unbalanced, a simulation model as shown in Fig. 7 is used.

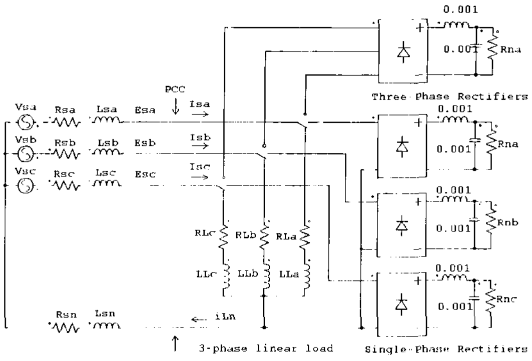


Fig. 7. Simulation circuit model for testing the defined power quality factors.

Three key switches are used to select the load types between linear and nonlinear loads. The linear loads are comprised with three R-L loads. There are two types of the nonlinear loads; one type with a three-phase rectifier, the other type with three single-phase rectifiers. The three-phase rectifier has a resistive load of Rna. Each of the three single-phase rectifiers has resistive loads of Rna, Rnb, and Rnc respectively. The dc-link filter in each rectifier has 1 [mH] inductance and 1000 [μF] capacitance With the proposed simulation circuit model, 19 different circuit conditions were simulated to evaluate the power qualities by the 7 major power quality factors defined in Table 7. Simulations were performed by PSIM V4.1.

Table 8 and 9 show the various circuit conditions and the calculated power quality factors. Table 8 is the case of linear loads. Table 9 is the case of nonlinear loads.

In the top row sector of each table; the 34 means 3-phase 4-wire systems, the 11 means single-phase systems. For the system voltages; the BV means balanced voltages, the UV means unbalanced voltages, the ZV means that zero-sequence components are included in the system voltages, the HV means that harmonic components are included in the system voltages.

The three phase voltages are 120 [Vrms] in 34BV. The a-phase voltage is reduced to 80 [Vrms] in 34UV that means the system voltage is unbalanced about 8.0[%]. The 3^{RD} harmonic voltage usually becomes zero-sequence component in three-phase systems. The magnitude of the 3^{RD} harmonic voltage is 1/3 times the fundamental voltage

When the loads have no neutral-line such as in three-phase full-bridge rectifiers in three-phase four-wire systems, the 3^{RD} harmonic voltage contributes to the

Table 8. Simulation conditions and results; Linear Loads.

Linear Loads		34BV -BLL	34BV -ULL	34UV -BLL	34UV -ULL	34ZV -BLL	34ZV -ULL	34HV -BLL	34HV -ULL	11BV -BRL	11BV -BLL
Source Voltages	Va 50 [Hz]	120∠0	120∠0	80∠0	80∠0	120∠0	120∠0	120∠0	120∠0	120∠0	120∠0
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠0	40∠0	0	0
	Vb 50 [Hz]	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	-	-
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠-120	40∠-120	-	-
	Vc 50 [Hz]	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	-	-
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠-240	40∠-240	-	-
Loads R & L	Ra [Ω]	5	15	5	15	5	15	5	15	5	5
	Rb [Ω]	5	5	5	5	5	5	5	5	-	-
	Rc [Ω]	5	3	5	3	5	3	5	3	-	-
	La [mH]	14	14	14	14	14	14	14	14	0	14
	Lb [mH]	14	14	14	14	14	14	14	14	-	-
	Lc [mH]	14	14	14	14	14	14	14	14	-	-
Power Quality Factor	DISF [%]	75	72	76	72	74	71	74	67	100	75
	APDF [%]	0	0	0	2	0	1	1	7	0	0
	TPDF [%]	0	55	26	62	32	59	45	65	70	79
	TPUF [%]	0	55	26	62	0	53	45	62	70	79
	TPHF [%]	0	0	0	0	32	27	0	17	0	0
	FPTF [%]	75	60	73	57	70	57	65	50	72	61
	TPTF [%]	75	60	74	58	70	57	66	54	72	61

Table 9. Simulation conditions and results; Nonlinear Loads.

Nonlinear Loads		34BV -BNL	34BV -UNL	34UV -BNL	34UV -UNL	34ZV -BNL	34ZV -UNL	34HV -BNL	11BV -BNL	11HV -BNL
Source Voltages	Va 50 [Hz]	120∠0	120∠0	80∠0	80∠0	120∠0	120∠0	120∠0	120∠0	120∠0
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠0	0	40∠0
	Vb 50 [Hz]	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	120∠-120	-	-
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠-120	-	-
	Vc 50 [Hz]	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	120∠-240	-	-
	[V_{RMS}] 150 [Hz]	0	0	0	0	40∠0	40∠0	40∠-240	-	-
Loads Rn	Rna [Ω]	5	15	5	15	5	15	5	5	5
	Rnb [Ω]	5	5	5	5	5	5	-	-	-
	Rnc [Ω]	5	3	5	3	5	3	-	-	-
Power Quality Factor	DISF [%]	98	98	98	98	100	100	100	98	92
	APDF [%]	0	0	2	2	0	0	15	0	26
	TPDF [%]	70	76	73	75	73	80	82	89	83
	TPUF [%]	0	46	27	48	0	42	66	77	30
	TPHF [%]	70	61	68	58	73	68	48	44	78
	FPTF [%]	70	64	67	65	69	61	51	46	45
	TPTF [%]	70	64	67	65	69	61	58	46	57

voltage unbalance and the 2ND harmonics. In this case the unbalance factor becomes about 22.5 [%], and the 2ND harmonic becomes about 2.0 [%].

For the load sides; the BRL means balanced pure resistive loads, the BLL means balanced linear resistive and inductive loads, the ULL means unbalanced linear resistive and inductive loads, the BNL means balanced nonlinear loads, the UNL means unbalanced nonlinear loads.

The resistance and inductance in each phase is 5 [Ω and 14 [mH] in BLL. Each phase of the load resistance changes to Ra=15 [Ω], Rb=5 [Ω], and Rc=3 [Ω] in ULL The resistance of each phase is 5 [Ω] in BNL. Each phas of the load resistances changes to Rna=15 [Ω], Rnb=5 [Ω and Rnc=3 [Ω] in UNL.

Although not simulated here, if the three-phase load are balanced and pure-resistive in a balanced sinusoida three-phase systems, all the seven power quality factor will be ideal values such as DISF=100 [%], APDF=0 [%], TPDF=0 [%], TPUF=0 [%], TPHF=0 [%], FPTF=100 [%], and TPTF=100 [%].

Compared to this, when the load is pure-resistive in sinusoidal single-phase systems, the factors DISP, APDF and TPHF are still ideal values, but the other factors are no more ideal values (eg. TPDF=70 [%] and TPTF=72 [%]), which means that the apparent power carries almost the same amount of useful active power *P* and useless alternating power *T*. This shows that three-phase systems are more efficient to transfer electrical energy than single-phase systems.

The displacement factors DISF in both 34BV-BLL and 11BV-BLL are 75 [%]. This is the same value calculated by the traditional definition of power factor in R-L loads. When the system voltages are distorted, DISF tends to decrease as can be seen in the cases of 34BV-ULL, 34UV-ULL, 34ZV-BLL, 34ZV-ULL, 34HV-BLL, and 34HV-ULL.

The active power distortion factor APDF increases from the ideal value when the system voltages are unbalanced or distorted by the harmonics. Comparing the cases between balanced linear loads (BLL) and unbalanced linear loads (ULL), the factor APDF becomes large in the case of ULL since the unbalanced loads generate more distorted active power by interacting with the distorted system voltage component.

Comparing the cases between the 34ZV and the 34HV, the factor APDF is larger in the case of the 34HV even though the 3^{RD} harmonic voltage is the same in both cases. This comes from the fact that the 3^{RD} harmonic voltages are converted to a very large amount of reverse-sequence voltage component among the three phase-lines in the case of the 34HV, while the 3^{RD} harmonic voltages become a zero-sequence voltage in the neutral-line where relatively small amount of current flows in the case of 34ZV. If the loads are nonlinear (BNL or UNL), the factor APDF becomes larger. Although, the factor APDF usually has no significant meaning in nonlinear loads such as rectifiers.

The circuit 34BV-BLL that has balanced voltage and balanced linear R-L loads is free from unbalance or harmonics since the total power distortion factor TPDF is zero. But the circuits 11BV-BRL and 11BV-BLL that also have linear load are heavily distorted by the unbalance since the total power unbalanced factor TPUF is more than 70 [%]. Even though the source voltages are the same in the cases of 11BV-BRL and 11BV-BLL, the circuit 11BV-BLL is worse than the circuit 11BV-BRL because the R-L loads interacts with the unbalanced single-phase voltage and make the system worse. The circuits of 34BV-ULL, 34UV-BLL, 34UV-ULL, and 34HV-BLL are also distorted by pure unbalance, since the total power harmonic factors TPHF are all zeros but the total power unbalanced factors TPUF exist in those cases.

The circuit 34ZV-BLL is distorted by pure harmonic with the factor of TPHF=32 [%] since the 3^{RD} harmonic component exists in the source voltages. The circuit 34ZV-ULL is distorted by both unbalance and harmonic with the factors of TPUF=53 [%] and TPHF=27 [%] since the source voltages are distorted by 3^{RD} harmonics and the linear R-L loads are unbalanced.

In the case of 34HV-BLL, the power distortion seems to result only from system unbalance with the factor of TPUF=45 [%], since the source voltage is unbalanced at about 22.5 [%] and distorted very slightly by the 2^{ND} harmonics at about 2.0 [%]. Though in the case of 34HV-ULL, the total power harmonic factor TPHF also exists since the unbalanced loads interacts with the 2^{ND} harmonic of the source voltages and generates the 4^{Th} order frequency of the power component.

The total power harmonic factor TPHF appears in all the cases of nonlinear loads, -BNL and -UNL. When the source voltages and the nonlinear loads are balanced as in the cases of 34BV-BNL and 34ZV-BNL, the factor TPHF exists while the factor TPUF is zero, which means the system is distorted by pure harmonics.

It is interesting to note that the total power transfer factor TPTF is better in the case of 11HV-BNL than in case of 11BV-BNL, 57 [%] to 46 [%]. The total power distortion factor TPDF is decreased by injecting the 3^{RD} harmonic to the source voltage in single-phase systems which have nonlinear loads.

6. Conclusion

This paper has defined on powers both in the time domain and in the frequency domain for single-phase systems and three-phase systems consistently. The powers maintain the conservation law. Power was decomposed into active, interactive and alternating power both in the time domain and in the frequency domain. The active power was decomposed into forward-sequence active power, reverse-sequence active power, and harmonic active power.

This paper showed that the conventional reactive power in sinusoidal single-phase systems is classified into the alternating power and the conventional reactive power in balanced sinusoidal three-phase systems is classified into the interactive power.

Several useful power quality factors were defined to identify and evaluate the power quality for the various circuit conditions. The simulation results verified that the proposed power quality factors evaluate and classify the various circuit conditions very clearly.

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References

[1] L.S.Czarnecki, "What is Wrong with the Budeanu Concept of Reactive and Didtortion Powers and Why It Should Be Abandoned", *IEEE Trans. IM-36, no. 3*, pp. 834~837, Sept. 1987.

[2] L.S.Czarnecki, "On Some Deficiencies of Fryze`s Approach to Describing Power Properties of Systems under Nonsinusoidal Condition", *Proc. of IEEE ICHPS VI, Bologna*, pp. 360~364, Sept. 21-23, 1994.

[3] W.Shepherd, P.Zakihani, "Suggested Definition of Reactive Power for Non-sinusoidal Systems," *Proceedins of IEE, vol. 119*, pp. 1361~1362, Sept. 1972.

[4] D.Sharon, "Reactive Power Definitions and Power-Factor Improvement in Nonlinear Systems", *Proceedings of IEE*, vol. 120, pp. 704~706, June 1973.

[5] N.L.Kusters, W.J.M.Moore, "On the Definition of Reactive Power under Non-sinusoidal Conditions", *IEEE Trans. PAS-99*, pp. 1845~1854, Sept./Oct. 1980.

[6] L.S.Czarnecki, "Orthogonal Decomposition of the Current in a Three-Phase Nonlinear Asymmetrical Circuit with Nonsinusoidal Voltage", *IEEE Trans. IM-37, no.1*, pp. 30~34, Mar. 1988.

[7] A.Ferrero, G.Superti-Furga, "A New Approach to the Definition of Power Components in Three-Phase Systems Under Nonsinusoidal Conditions", *IEEE Trans. on IM-40, No.3*, pp. 568~577, June 1991.

[8] P.S.Filipski, "Apparent Power-A Misleading Quantity in the Nonsinusoidal Power Theory. Are All Nonsinusoid: Power Theories Doomed to Fail?", *Internationc Workshop on Power Definitions & Measurement*, 1991, p 39~47.

[9] A.E.Emannuel, "The Buchholz-Goodhue Apparent Powe Definition: The Practical Approach for Nonsinusoidal ar Unbalanced Systems", *IEEE Trans. PD-13, no.2*, pp. 34 ~349, Apr. 1998.

[10] H.S.Kim, H.Akagi, "The Instantaneous Power Theory c the Rotating p-q-r Reference Frames," *Conferenc Records of IEEE/PEDS '99*, pp. 422~427, July 1999.

[11] H.S.Kim, F.Blaabjerg, and B.Bak-Jensen, "Spectr: Analysis of Instantaneous Powers in Single-phase an Three-phase Systems with Use of p-q-r Theory' *Conference Records of IEEE/PESC'01*, CD ROM, Jun 2001.

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